

PATENT APPLICATION

5

of

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for

Solid Catadioptric Lens with a Single Viewpoint

FIELD OF THE INVENTION

15 The present invention relates generally to lenses for applications such as vision and imaging where a single viewpoint is required, and in particular to catadioptric lenses having a single viewpoint.

BACKGROUND OF THE INVENTION

20 Applications in computational vision such as ego-motion estimation and tracking often require imaging a large field of view. It is also desirable for an imaging system to have a single viewpoint in order to produce geometrically correct perspective images from the panoramic images obtained from
25 the imaging system. The single and fixed viewpoint constraint requires that an imaging system only capture light that is passing through a single point in three dimensional

space, thus sampling the 5-dimensional plenoptic function at that point, which is known as the effective viewpoint. Such imaging systems have been realized by assemblies of curved mirrors and lenses. Although these catadioptric systems can 5 have a large field of view and can satisfy the single viewpoint requirement they are cumbersome, expensive and large.

A number of wide field of view optics use facing mirrors to 10 produce high quality images at the expense of an obscuration of the field of view. A simple example of a prior art optical system **10** of such type is shown in Fig. 1. System **10** has two facing mirrors **12**, **14** aligned on an optical axis **16**. Mirror **14** receives and reflects light from a scene **20** to 15 mirror **12**. Mirror **12** reflects the light back to mirror **14** such that the light passes a central aperture **18** in mirror **14** and projects an image **22** of scene **20** on a screen **24**.

Mirror **12** obscures a cone-shaped central portion **26** of the 20 field of view seen by mirror **14**. The result of this obscuration is a shadow **28** in image **22**. To be imaged, light arriving from scene **20** has to be incident on mirror **14** at an angle larger than the angle of cone **26**, e.g., at an angle of incidence θ_i relative to axis **16**.

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The prior art contains teachings about telescopes and other systems that employ the above-described principles. For example, U.S. Pat. No. 5,089,910 to Sigler teaches a catadioptric zoom relay telescope with two mirrors of which

the first mirror or primary mirror is aspheric. U.S. Pat. No. 5,940,222 to Sinclair et al. teaches catadioptric zoom lens assemblies employing these same principles.

5 Some applications such as robot vision and panoramic imaging require the optical system to have a single point of view or viewpoint. This condition enables the optical system to produce a perspective view of objects in its field of view.
10 In some applications, it is further desirable to maximize the size of the field of view imaged from the single viewpoint.

It is difficult to satisfy all of the above conditions with a single system. The catadioptric zoom relay telescopes and lens assemblies are usually limited to a small field of view
15 and many do not have a single viewpoint. In fact, many high quality systems offer excellent on-axis performance, e.g., as taught by Hicks in U.S. Pat. No. 6,412,961 but are inherently not single viewpoint. U.S. Pat. No. 5,473,474 to Powell teaches a panoramic lens that images a large field of view
20 but lacks a single viewpoint. Still another approach using the facing mirrors configuration is taught by Kuroda et al. in U.S. Pat. No. 5,854,713. This patent describes a reflection type angle of view transforming optical apparatus that is hollow but also lacks a single viewpoint. Of further
25 interest is the catadioptric system of Charles shown in U.S. Pat. No. 6,449,103. Additional references of interest include U.S. Pat. No. 4,566,763 teaching the use of a parabolic reflector and U.S. Application No. 2003/0142203 teaching the use of a hyperbolic reflector.

The prior art does teach some systems that have a single viewpoint. For example, U.S. Pat. No. 3,505,465 to Rees discloses how to use a hyperbolic mirror to produce a single viewpoint system for a person viewing an image such as a TV or video image produced, e.g., by a video camera. More recently, Patent Nos. 5,760,826 and 6,118,474 to Nayar describe an imaging apparatus for imaging a scene with a substantially paraboloid-shaped reflector whose focus is coincident with the single viewpoint. The imaging apparatus has a telecentric means optically coupled to the paraboloid-shaped reflector for filtering out principal rays of electromagnetic radiation that are not orthographically reflected by the paraboloid-shaped reflector.

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Unfortunately, none of the prior art teachings provide a compact, effective and easy to manufacture single viewpoint lens that can be used in vision systems requiring a panoramic projection or perspective view of objects distributed over a large field of view.

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OBJECTS AND ADVANTAGES

In view of the above, it is an object of the invention to provide a compact, effective, rugged and easy to manufacture 25 catadioptric lens with a single viewpoint and a large field of view. In particular, it is an object of the invention to provide a single viewpoint catadioptric lens that can be used in vision systems such as vision systems requiring a panoramic projection.

These and other objects and advantages of the invention will become apparent upon reading the ensuing description.

SUMMARY OF THE INVENTION

5 The objects and advantages of the invention are secured by a solid catadioptric lens with a single point of view or viewpoint. The lens has an optical axis and a spherical refractive surface with a center C on the optical axis. The lens has an ellipsoidal reflective surface facing the
10 spherical refractive surface arranged such that a first focus F₁ of the ellipsoidal reflective surface is coincident with the center C of the spherical refractive surface. The single viewpoint of the lens is at the center C of the spherical reflective surface. Further, the lens has a shaping surface
15 facing the ellipsoidal reflective surface for shaping a light that passes the single viewpoint.

In one set of embodiments the shaping surface is a refractive shaping surface and the lens has an aperture for enforcing
20 the single viewpoint at center C. The aperture is positioned at a second focus F₂ of the ellipsoidal reflective surface. The lens is constructed such that the second focus F₂ of the ellipsoidal reflective surface is on the optical axis, like first focus F₁.

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In some embodiments where the shaping surface is a refractive shaping surface, the second focus F₂ is located near or even on the refractive shaping surface. In some other embodiments

using a refractive shaping surface, the second focus F_2 is inside the lens. The refractive shaping surface can assume a variety of shapes, but it is preferably ellipsoidal, thus forming an ellipsoidal refractive shaping surface. For light 5 shaping reasons, it is also preferred that the ellipsoidal refractive shaping surface have its first focus F_1' coincident with the second focus F_2 of the ellipsoidal reflective surface. In some embodiments, it is also convenient that the ellipsoidal refractive shaping surface have a conic constant 10 K_2 equal to a conic constant K_1 of the ellipsoidal reflective surface.

In another set of embodiments the shaping surface is a reflective surface and an aperture is used for enforcing the 15 single viewpoint. For example, in some embodiments in this set the aperture is positioned on the ellipsoidal reflective surface. In alternative embodiments, the aperture is positioned beyond the ellipsoidal reflective surface. Again, for light shaping reasons the reflective surface is 20 preferably a second ellipsoidal reflective shaping surface. Furthermore, in some specific embodiments the second ellipsoidal reflective shaping surface has a first focus F_1' coincident with the second focus F_2 of the ellipsoidal reflective surface. In some of these specific embodiments 25 the second ellipsoidal reflective shaping surface has a conic constant K_2 equal to the conic constant K_1 of the ellipsoidal reflective surface.

It should be noted that whether the shaping surface is refractive or reflective it can assume various shapes including conic sections. Alternatively, the shaping surface can be flat. Furthermore, the shaping surface does not have 5 to be only refractive or reflective; it can be semi-transparent.

The solid catadioptric lens is preferably made of a optical material with an index n. Suitable materials include 10 glasses, plastics and other well-known optical materials.

The invention further provides for a single viewpoint vision system. The vision system employs the solid catadioptric lens for shaping light passing through the single viewpoint. 15 It should be noted that the vision system can be used for projecting light or for collecting light for functions such as scanning or imaging, respectively. In embodiments where the lens is used for imaging, an imaging element can be provided for imaging the light onto an imaging unit or screen 20 in an imaging plane. In scanning applications a scanning arrangement is provided.

In some embodiments an optical relay is used for passing the light from the lens to the application. For example, an 25 optical relay can be used to pass the light to an imaging plane when the lens is deployed in an imaging vision system. In scanning vision systems, an optical relay can be used to deliver light from a scan element, e.g., a scan mirror to the lens.

The details of the invention will now be explained in the detailed description with reference to the attached drawing figures.

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BRIEF DESCRIPTION OF THE DRAWINGS

- Fig. 1 (Prior art) is a three-dimensional diagram illustrating a class of off-axis optical systems.
- 10 Fig. 2 is a cross-sectional side view of one embodiment of a lens according to the invention.
- Fig. 3 is a cross-sectional side view of the lens of Fig. 2 used in imaging.
- 15 Fig. 4 is a cross-sectional side view illustrating another embodiment of a lens according to the invention.
- Fig. 5 is a cross-sectional side view of a lens according to the invention with folded geometry.
- 20 Fig. 6 is a cross-sectional side view of another lens with folded geometry.
- Fig. 7 is a cross-sectional side view of a folded lens used for projecting or imaging.
- 25 Fig. 8 is a three-dimensional diagram showing a vision system having an imaging element and employing the lens of Fig. 7.
- Fig. 9 is cross-sectional side view showing another vision system having a scanning arrangement and employing the lens of Fig. 7.
- Fig. 10 is a cross-sectional side view of yet another lens according to the invention.

Fig. 11 is a cross-sectional side view of the lens similar to the one shown in Fig. 2 with an optical relay.

DETAILED DESCRIPTION

- 5 The present invention will be best understood by first referring to an embodiment of a single viewpoint solid catadioptric lens **30** as shown in Fig. 2 in cross-sectional side view. Lens **30** has an optical axis **32** and is made of an optical material of index n. Preferably, the optical
10 material is uniform and exhibits substantially no or very little variation of index n. Suitable materials include glasses and plastics, such as moldable plastics and other optical materials.
- 15 Lens **30** has a spherical refractive surface **34** with a center C on optical axis **32**. A light **36** propagating to and a light **36'** propagating from center C traverses spherical refractive surface **34** at normal incidence. Spherical refractive surface **34** defines a solid angle Θ over which lens **30** gathers light
20 **36** and into which lens **30** projects light **36'**.

Lens **30** has an ellipsoidal reflective surface **38** facing spherical refractive surface **34**. Ellipsoidal reflective surface **38** can be made reflective by providing it with a reflective coating or film **40**, as shown in this embodiment, or by other means. Ellipsoidal reflective surface **38** is created by revolving a mathematical ellipse, as shown in dashed lines **38'**. Specifically, surface **38** is defined by revolving ellipse **38'** about optical axis **32**. Surface **38** is

oriented such that a first focus F_1 is coincident with center C of spherical refractive surface **34** on optical axis **32**. Second focus F_2 defined by surface **38** is also on optical axis **32** and within lens **30**.

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Lens **30** has a shaping surface **42** facing ellipsoidal reflective surface **38** for shaping light **36**, **36'** passing through center C. In fact, center C is the point of view or viewpoint of lens **30**. An aperture **44** is provided to ensure 10 that center C is the only viewpoint of lens **30**. In other words, aperture **44** enforces the single viewpoint of lens **30**. Preferably, aperture **44** is formed by an object embedded in the optical material of lens **30** and having a pin-hole or diaphragm at second focus F_2 . Alternatively, aperture **44** is 15 defined in a non-transparent section of the optical material of lens **30**. A person skilled in the art will appreciate that there are many alternative ways of defining aperture **44**.

Shaping surface **42** can assume any shape and be located at any 20 position past or even at aperture **44**, as found suitable for shaping light **36**, **36'** for a given application. In the present embodiment shaping surface **42** is a refractive shaping surface for passing light **36**, **36'** in and out of lens **30**. In fact, refractive shaping surface **42** is an ellipsoidal refractive shaping surface formed by revolving a mathematical ellipse **42'**, as shown in dashed lines, about optical axis **32**. For light shaping reasons, it is preferred that ellipsoidal refractive shaping surface **42** have its first focus F_1' 25 coincident with second focus F_2 defined by surface **38**, and its

second focus F_2' on optical axis 32 within lens 30. Even more preferably, surface 42 has a conic constant K_2 equal to:

$$K_2 = -\frac{1}{n^2},$$

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where n is the index of the optical material. Under these circumstances, light 36 entering lens 30 over solid angle Θ emerges from lens 30 through surface 42 in a direction substantially parallel to optical axis 32. It is further 10 possible to set a conic constant K_1 of surface 38 equal to conic constant K_2 , as in the present embodiment.

A plate 46 is placed before lens 30. When lens 30 collects light 36 arriving at an angle of incidence θ_i to optical axis 15 32, then plate 46 can be a screen for projecting light 36 thereon. In this mode lens 30 can be used for imaging. Alternatively, plate 46 emits light 36' substantially parallel to optical axis 32 into lens 30. In this mode lens 30 projects light 36' into solid angle Θ and can be used for 20 projecting an image.

The operation of lens 30 for imaging a wide field of view is explained with reference to the cross-sectional side view of Fig. 3. The field of view is defined by solid angle Θ over 25 which lens 30 gathers light 36. Note that angle Θ is symmetric about optical axis 32.

Lens 30 is positioned such that its single viewpoint at center C is at a height h above an object plane 48. A number of object points P_1 , P_2 , P_3 , P_4 are located on object plane 48 (points P_3 and P_4 are far away from optical axis 32 on plane 48). Light 36 emanates from object plane 48 and propagates in ray bundles 50, 52, 54 and 56 to lens 30. Point P_1 lies at one edge of the field of view such that ray bundle 50 emanating from it enters lens 30 at minimum incidence angle θ_{\min} . Point P_4 lies at the other edge of the field of view such that ray bundle 56 emanating from it enters lens 30 at maximum incidence angle θ_{\max} . The design of lens 30 enables maximum incidence angle θ_{\max} to be nearly 90° . Ray bundles 50 and 56 are drawn in dashed lines to indicate that they bound the field of view of lens 30.

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Ray bundles 50, ... 56 enter lens 30 via spherical refractive surface 34. They then pass through the single point of view at center C and propagate to reflective ellipsoidal surface 38. At surface 38 ray bundles 50, ... 56 are reflected to ellipsoidal refractive shaping surface 42. Aperture 44 enforces the single point of view by allowing ray bundles 50, ... 56 to continue propagating to ellipsoidal refractive shaping surface 42 while stopping light that enters via spherical refractive surface 34 but does not pass through the single point of view at center C.

Since conic constants K_1 and K_2 of surfaces 38 and 42 are equal, and $K_1=K_2=-1/n^2$, and foci F_2 and F_1' coincide, light 36 of ray bundles 50, ... 56 is substantially parallel to optical

axis **32** upon exiting lens **30**. This is a desirable type of shaping because ray bundles **50**, ... **56** are projected onto image plane **46** without requiring further optical shaping. Points P_1 , ... P_4 on object plane **48** are thereby imaged to corresponding imaged points P'_1 , ... P'_4 on image plane **46**.

An advantageous feature of lens **30** is that ray bundles **50**, ... **56** impinging on refractive surface **34** at equal angular intervals or field angles are mapped substantially linearly to distances from optical axis **32** when exiting ellipsoidal refractive shaping surface **42**. This means that object points P_1 , ... P_4 at equal field angles are mapped to imaged points P'_1 , ... P'_4 at substantially equal separations from each other in image plane **46**. The substantially linear map between field angle and distance from optical axis in image plane **46** is useful in many imaging applications and is sometimes referred to as $f\text{-}\theta$ imaging.

Fig. 4 is a cross-sectional side view of another embodiment of a single viewpoint catadioptric lens **60**. Lens **60** is made of a moldable plastic of index n and has a spherical refractive surface **62** with a center C on an optical axis **64**. Surface **62** faces an ellipsoidal reflective surface **66**. The two surfaces are arranged such that a first focus F_1 defined by surface **66** coincides with center C. A shaping surface **68** faces surface **66**. In this embodiment shaping surface **68** is reflective and is parabolic-shaped, thus forming a paraboloid reflective shaping surface. Surface **68** is defined by a single focus F_1' lying on optical axis **64**. Moreover, focus

F_1' coincides with a second focus F_2 of surface 66. In this embodiment conic constants K_1 and K_2 of surfaces 66 and 68 are not equal.

5 Lens 60 has an aperture 70 for enforcing the single viewpoint at center C. Since light cannot pass through paraboloid reflective shaping surface 68, aperture is positioned at facing surface 66. In the present embodiment aperture 70 is defined in or on ellipsoidal reflective surface 66. For
10 example, aperture 70 is a pin-hole in a reflective coating or film covering surface 66. Alternatively, aperture 70 can be placed beyond surface 66 or before it.

A projecting unit 72 for emitting light 36' is positioned
15 behind surface 66 and centered on optical axis 64. Unit 72 can be an array of light emitters and is used herein to illustrate the application of lens 60 for projecting light 36' into the field of view indicated by angle Θ . The field of view defines a minimum emission angle $\sigma_{\min.}$ and a maximum
20 emission angle $\sigma_{\max.}$. Unit 72 emits light 36' from its emitters such as a pixel 74 far enough from optical axis 64 to map to an emission angle σ such that $\sigma_{\min.} < \sigma < \sigma_{\max.}$. For example, light 36' emitted from a pixel 74 at a distance d to optical axis 64, is admitted into lens 60 through aperture 70 and emitted at emission angle σ . A person skilled in the art will recognize that additional optical elements such as lenses and mirrors can be placed between surface 66 and unit 72 for performing various light shaping and guiding functions as may be required for any particular application.

In one application, lens **60** is used for projecting light **36'** into its field of view. Unit **72** activates pixel **74** for emitting light **36'** at emission angle σ to optical axis **64**.
5 Light **36'** propagates parallel and offset by distance d to optical axis **64** and is admitted into lens **60** via aperture **70**. The light guiding properties of lens **60** map light **36'** to angle σ as it exits lens **60** through spherical refractive surface **62**.

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In another application lens **60** is used for collecting light **36** arriving from the field of view, e.g., at an angle of incidence $\theta_i=\sigma$, where angle of incidence θ_i is larger than a minimum incidence angle $\theta_{\min.}=\sigma_{\min.}$ and smaller than a maximum
15 incidence angle $\theta_{\max.}=\sigma_{\max.}$.

The geometry of the single viewpoint catadioptric lens of the invention can be modified in many ways. For example, the ellipsoidal surfaces of the lens can be folded. Fig. 5
20 illustrates an embodiment of a folded single viewpoint catadioptric lens **80** having external profiles **82** and **84**. Lens **80** has a spherical refractive surface **86** with a center C coincident with the single viewpoint. An ellipsoidal reflective surface **88** having a first focus F_1 and a second
25 focus F_2 faces surface **86** and its first focus F_1 is coincident with center C. A shaping surface **90**, here in the form of a second reflective ellipsoidal shaping surface having first and second foci F_1' , F_2' faces surface **86**. All foci are on an optical axis **87**.

Ellipses **92**, **94** that are revolved to form surfaces **88** and **90** are indicated in dashed lines for clarification. In contrast to previous embodiments, ellipse **94** has its second focus F_2' 5 on the other side of the viewpoint or center C and even beyond surface **88**. The overlap of ellipses **92**, **94** and surfaces **88**, **90** created by their revolution produces a geometry that is herein referred to as folded.

10 Second reflective ellipsoidal shaping surface **90** is formed on external profile **82** with the aid of a reflective coating or film (not shown). The size of surface **90** can be decreased to enlarge the field of view of lens **80**. External profile **84** extends from surface **88** and terminates at a flat coupling 15 face **96**. Face **96** is transparent and located such that second focus F_2' of surface **90** falls on it. In fact, the size of face **96** defines the aperture of lens **80** that enforces the single viewpoint at center C. If a small aperture is desired, then a mask can be supplied on face **96** and a central 20 opening in the mask can define the aperture.

To understand the operation of lens **80** we follow an incident ray bundle **98** of light **36** entering lens **80**, while realizing that lens **80** can also project light **36'**. Light **36** enters 25 lens **80** through surface **86**, passes single viewpoint at center C and is reflected by surface **88**. Light **36** then propagates to second focus F_2 as mathematics dictate that light passing through one focus of an ellipsoid and internally reflected converge at its second focus. By design, second focus F_2 is

coincident with first focus F_1' of surface **90** that is also ellipsoidal and thus enforces the same mathematical rule on light **36**. Specifically, light **36** is reflected from surface **90** and converges at second focus F_2' on coupling face **96**.

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Light **36** is out-coupled through face **96** and may be further shaped, deflected and/or steered as required by the deployment conditions of lens **80**. For example, imaging elements can be positioned past face **96** to guide light **36**
10 into an image plane. Alternatively, optical relays can be positioned there to shape and guide light **36**.

Another folded geometry is embodied by a catadioptric lens **100** shown with its ray-trace in Fig. 6. The basic geometry
15 of lens **100** is described by nine geometric design parameters: R , R_1 , K_1 , R_2 , K_2 , L_1 , L_2 , L_3 , and L_4 . The first five of these represent: radius of spherical refractive surface **102**, radius of curvature of ellipsoidal reflective surface **104**, conic constant of surface **104**, radius of curvature of second
20 ellipsoidal reflective shaping surface **106**, conic constant of surface **106**. Parameters L_1 , L_2 , L_3 , and L_4 correspond to lengths as shown. Additionally, **108** is an apex of surface **106**, **110** is an apex of surface **104**, and **112** is an aperture enforcing the single viewpoint of lens **100**. Note that second
25 focus F_2' of surface **106** falls on surface **104** within aperture **112**. Note that surface **106** is on an external profile **118** in this embodiment.

The design of lens 100 is a complete closed form solution. Thus, the optical performance of any vision system using lens 100 mostly depends on the design of its optical relay. In 5 the present embodiment a single relay lens 114 represents an optical relay for producing images at a single wavelength of light 36 in an image plane 116. A more achromatic optical relay with a field flattener can be used for color imaging, as will be appreciated by a person skilled in the art.

10 Lens 100 can be scaled to different sizes by changing the values of R, R₁ and R₂. The general shape of lens 100 and its angular magnification is controlled by the ratio of the parameters K₁ and K₂. Once these parameters have been adjusted, then the following equations are used to find L₁, 15 L₂, L₃ and L₄:

$$L_1 = R_1 \frac{[1 - \sqrt{-K_1}]}{1 + K_1};$$

$$L_2 = \frac{2R_1\sqrt{-K_1}}{1 + K_1};$$

$$L_3 = \frac{R_2[1 - \sqrt{-K_2}]}{1 + K_2};$$

$$L_4 = \frac{2R_2\sqrt{-K_2}}{1 + K_2}.$$

20 This ensures that the first geometrical focus F_{1'} of second ellipsoidal reflective shaping surface 106 is coincident with second geometrical focus F₂ of ellipsoidal reflective surface 104. The present embodiment illustrates a special case where

$L_4 = L_1 + L_2$, superposes second geometrical focus F_2' of second ellipsoidal reflective shaping surface **106** on apex **110** of ellipsoidal reflective surface **104**. As noted above, this causes aperture **112**, which may have a diameter of 2 mm or even less, depending on the desired light intensity, to fall on apex **110**. Preferably, aperture **112** is just a portion of ellipsoidal reflective surface **104** that is masked off before coating entire surface **104** with a reflective coating such as aluminum.

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Fig. 7 illustrates still another folded single viewpoint lens **120** without any external profiles and a field of view described by solid angle Θ . Lens **120** has a spherical refractive surface **122** facing an ellipsoidal reflective surface **124** such that a center C of surface **122** is coincident with first focus F_1 of surface **124**. Surface **124** faces a semi-transparent ellipsoidal shaping surface **126** such that a second focus F_2 of surface **124** is coincident with a first focus F_1' of surface **126**. Second focus F_2' of surface **126** falls on surface **124** within an aperture **128**. Center C and all foci are on an optical axis **130** of lens **120**.

An optical relay **132** is positioned next to surface **124** for guiding light **36'** generated by a display unit **134** to lens **120**. More precisely, relay **132** is a telecentric relay for guiding light **36'** that propagates parallel to optical axis **130** into lens **120**. Relay **132** converts a distance d at which light **36'** is offset from optical axis **130** to an admission angle α into lens **120**. Reference f indicates a focal length

of relay 132. By virtue of the design of relay 132, admission angle α is a substantially linear function of distance d over small values of angle α .

5 During operation, a pixel 136 of display unit 134 offset by distance d from optical axis 130 generates light 36'. Relay 132 guides light 36' into lens 120 at admission angle α . Light 36' is reflected from semi-transparent surface 126, surface 124 and then exits lens 120 at an emission angle σ through surface 122. During this process angle α is
10 "amplified" to angle σ and the angular magnification is given by the ratio σ/α . A portion 138 of light 36' exits lens 120 via semi-transparent surface 126. Portion 138 can be used for monitoring the operation of lens 120 and/or display unit
15 134. Portion 138 can also be used for verify alignment of lens 120 and display unit 134 or other functions. A skilled artisan will appreciate that the degree of transparency of semi-transparent surface 126 can be adjusted depending on these functions. It should also be noted that the
20 transparency of semi-transparent surface 126 can depend on wavelength of light 36'.

In an alternative embodiment, lens 120 operates in reverse by admitting light 36 and projecting it to pixel 136. In this
25 case display unit 134 is replaced by a light-sensing element, e.g., an imaging element such as an imaging array. In such array pixel 136 is light-sensitive. Note that a portion of light 36 is also transmitted through semi-transparent surface 126.

From the small sample of designs described above, it is clear that catadioptric lenses according to the invention are versatile, simple, rugged and easy to manufacture. They can
5 be made in parts or as a whole part by techniques such as molding. Their optical performance depends largely on the accuracy of the surfaces and the design of auxiliary optical relays that deliver light to or collect light from them. Such relays should be designed based on the vision system or
10 application and specific design choices may depend on whether it is a system with an imaging element, a scanning arrangement or a display element.

Fig. 8 illustrates a single viewpoint vision system **140** using
15 lens **120** with a reflective ellipsoidal shaping surface **126'** rather than semi-transparent shaping surface **126**. Vision system **140** has an imaging element **142**, e.g., an imaging array with pixels **144** (shown partially for clarity). Array **142** is positioned in an image plane **146** behind surface **124**. The
20 optical relay between surface **124** and image plane **146** is not shown here for reasons of clarity. However, any type of relay, including a telecentric relay as described in Fig. 7, can be used between lens **120** and imaging array **142**.

25 Surface **126'** limits the field of view of lens **120** to the off-axis region described by solid angle Θ . Therefore, vision system **140** is most useful when the center of the field of view is obscured or does not require imaging. The center of the field of view corresponds to shadow **148** in image plane

146. For clarity of explanation, aperture **128** for enforcing point of view C is not indicated on surface **124** and image plane **146** is shown enlarged.

5 Vision system **140** is directed at an arbitrary object **150** to be imaged. Herein, object **150** is a substrate whose surface lies in an X'-Y' plane of object coordinates (X', Y', Z') . Vision system **140** is above substrate **150** and the origin of object coordinates and single viewpoint C of lens **120** are
10 connected by a vector R^c . Vector R^c is collinear with optical axis **130** and the norm of vector R^c is the distance between the origin and viewpoint C. Vision system **140** moves in space and its coordinates (X, Y, Z) are rotated with respect to object coordinates (X', Y', Z') . Many conventions exist to align the
15 object coordinates and vision system coordinates. For example, the rotation between vision system coordinates (X, Y, Z) and object coordinates can be expressed by three consecutive rotations by Euler angles (φ, θ, ψ) .

20 During operation vision system **140** collects light **36**, such as light **36** from a point P on substrate **150**. Light **36** propagates in a ray bundle **152** to enter lens **120** at angle of incidence θ_i . Lens **120** images point P to an imaged point P^I on imaging array **142** in image plane **146**. Conveniently, image plane **146** is described by imaging array axes X^I and Y^I , and the location of imaged point P^I in image plane **146** is described by a vector R^p . Because of its single viewpoint C,
25 lens **120** produces a panoramic projection of imaged point P^I .

Thus, lens **120** can produce a panoramic image of object **150** in image plane **146**.

In a modified embodiment, vision system **140** can use lens **120** to project light **36'** to a projected point P_p on substrate **150** and collect light **36** from point P simultaneously. In this embodiment a pixel **154** at point P^s on array **142** produces light **36'**. The location of point P^s in image plane **146** is described by vector R^s . A ray bundle **156** of light **36'** is projected through lens **120** at emission angle σ onto substrate **150** to point P_p . Hybrid arrays having light sensitive and light-emitting pixels that can be employed in this embodiment are known in the art. Of course, a display unit such as the one shown in Fig. 7 can be used for projecting light **36'** if no imaging of substrate **150** is required.

Fig. 9 shows a vision system **160** employing lens **120** with a wavelength-dependent semi-transparent ellipsoidal shaping surface **126''** to project light **36'** on an object **162**. At certain points object **162** responds by producing a back-scattered light **36''** and system **160** simultaneously uses lens **120** to collect back-scattered light **36''**.

System **160** has a display unit **164**, e.g., a display screen or a detector array, in front of surface **126''**. Unit **164** is centered on optical axis **130**. Further, system **160** has a scanning arrangement **166** with a light source **168** for generating light **36'**. Arrangement **166** has a scan mirror **170** for deflecting or steering light **36'**. Mirror **170** is tilted

by a scan angle γ with respect to a mirror plane M_p . Drivers for controlling scan angle γ are well-known in the art.

Arrangement 166 has an optical relay 172 for shaping and 5 directing light 36' along optical axis 130 into lens 120 through aperture 128. Relay 172 is of the type that converts scan angle γ to a corresponding admission angle α into lens 120. For example, relay 172 is a 4-f system using two lenses with the same or different focal lengths on axis 130 such 10 that the center of mirror 170 is coincident with one focal point of relay 172 and second focus F_2' of surface 126" is coincident with another focal point of the 4-f system. Relay 172 also has a beam splitter 176 for deflecting any light returning to scanning arrangement 166 from lens 120.

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In operation, system 160 directs light 36' by adjusting scan angle γ of mirror 170. A change in scan angle γ changes emission angle σ at which light 36' exits lens 120. In the present case scan angle γ is varied such that light 36' is 20 first emitted at angle σ_1 and then at σ_2 .

The pass wavelength of semi-transparent surface 126" is chosen such that a small portion 174 of light 36', e.g., a fraction of a percent, is transmitted and projected onto 25 display unit 164. Specifically, when light 36' is emitted at angle σ_1 portion 174 is transmitted to point P'_2 . Then, at angle σ_2 portion 174 is transmitted to point P'_1 . Portion 174 of light 36' can be used for reference, feedback, tracking or other auxiliary functions.

At angle σ_2 object 162 produces back-scattered light 36" that returns to lens 120 along the path of light 36'. Light 36" enters lens 120 through surface 122 at an angle of incidence 5 $\theta_i=\sigma_2$. A small fraction of light 36" exits lens 120 via surface 126". The remainder of light 36" is reflected by surface 126" and is separated by beam-splitter 174. Of course, if the fraction of light 36" registered by unit 164 is sufficient for monitoring back-scattered light 36" then 10 the remainder of light 36" can be discarded. In those cases beam-splitter 174 can be removed.

Fig. 10 illustrates yet another embodiment of a single viewpoint lens 180. Lens 180 has a spherical refractive 15 surface 182 facing an ellipsoidal reflective surface 184, which in turn faces a flat refractive shaping surface 186. First focus F_1 of surface 184 and center C of surface 182 are coincident at the single viewpoint of lens 180. The second focus F_2 of surface 184 is on surface 186 and within aperture 20 188 enforcing the single viewpoint.

Lens 180 is made of two materials 183, 185 having indices n_1 , 25 n_2 respectively. Material 183 is preferably a glass or plastic, while material 185 is a glass or plastic, but could also be a liquid or optical gel filling a cavity in lens 180. In the latter case, a portion 190 of lens 180 indicated in dashed and dotted lines is made of a suitable material that can also be a glass or plastic forming an envelope to contain material 185. It is preferable that $n_1=n_2$.

An optical relay in the form of a compound lens **192** is positioned adjacent to surface **186** for out-coupling light **36** from lens **180**. In the present case lens **192** is designed for 5 projecting light **36** onto an image plane **194**. In reverse, lens **192** can be used for in-coupling light **36'** from image plane **194** into lens **180**.

Alternatively, lens **180** can be built with the aid of a shell 10 **196** indicated in dashed lines and defining an internal cavity **198**. Cavity **198** is filled, e.g., with an optical gel or other optical material. In fact, entire lens **180** including portion **190** can be a hollow form or shell filled with an optical material such as an optical gel or liquid.

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Fig. 11 is a cross-sectional side view of a lens **200** similar to lens **30** shown in Fig. 2 and equipped with an optical relay **210**. Lens **200** has a spherical refractive surface **202**, a facing ellipsoidal reflective surface **204** and a refractive 20 ellipsoidal shaping surface **206**. First focus F_1 of surface **204** and center C of surface **202** are coincident at the single viewpoint. Foci F_1' and F_2 are also coincident. All foci are on optical axis **208**.

25 Lens **200** differs from lens **30** in that it has no fixed aperture within its body. Rather, an adjustable aperture **212** is provided in optical relay **210** between lenses **214**, **216**. Lenses **214** and **216** have focal lengths f_1 and f_2 respectively. Relay **210** has a first image plane **218** at a distance equal to

f_1 from lens **214**. A second image plane **220** is located at a distance equal to f_2 from lens **216**. A person skilled in the art will realize that relay **210** is a type of 4-f relay.

- 5 During operation aperture **212** can be adjusted to regulate the F-number of lens **200** and operate in a wide range of illumination conditions. It should be noted that opening aperture **212** to obtain a low F-number results in progressive deterioration of the single viewpoint property of lens **200**.

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The single viewpoint catadioptric lens according to the invention admits of myriads of other embodiments. For example, it does not have to be a solid lens, but can also be hollow, e.g., in cases where it is made by molding. In some 15 cases where certain regions of the lens are hollow cavities left by the fabrication method, these hollow cavities can be filled with an optical fluid or gel having an index of refraction matching that of the solid sections of the lens. In still other embodiments the ellipsoidal reflective surface 20 and/or the shaping surface are counter-sunk within the lens rather than being on an external profile. Given all the alternative embodiments, the scope of the invention is to be judged by the following claims and their legal equivalents.